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Centrality dependence of the pseudorapidity density distribution for charged particles in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

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ABSTRACT

We present the charged-particle pseudorapidity density in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV in centrality classes measured by ALICE. The measurement covers a wide pseudorapidity range from −3.5 to 5, which is sufficient for reliable estimates of the total number of charged particles produced in the collisions. For the most central (0–5%) collisions we find $21\,400 \pm 1\,300$, while for the most peripheral (80–90%) we find 230 ± 38. This corresponds to an increase of $(27 \pm 4)\%$ over the results at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV previously reported by ALICE. The energy dependence of the total number of charged particles produced in heavy-ion collisions is found to obey a modified power-law like behaviour. The charged-particle pseudorapidity density of the most central collisions is compared to model calculations — none of which fully describes the measured distribution. We also present an estimate of the rapidity density of charged particles. The width of that distribution is found to exhibit a remarkable proportionality to the beam rapidity, independent of the collision energy from the top SPS to LHC energies.

1. Introduction

In ultra-relativistic heavy-ion collisions a dense and hot phase of nuclear matter is created [1–4]. This phase of QCD matter is considered to be a plasma of strongly interacting quarks and gluons and is therefore labelled the sQGP [5]. The multiplicity of primary, charged particles produced in heavy-ion collisions is a key observable to characterise the properties of the matter created in these collisions [6]. The study of the primary charged-particle pseudorapidity density ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$) over a wide pseudorapidity (η) range and its dependence on colliding system, centre-of-mass energy, and collision geometry is important to understand the relative contributions to particle production from hard scatterings and soft processes, and may provide insight into the partonic structure of the interacting nuclei.

We have previously reported measurements on primary charged-particle pseudorapidity densities over a wide pseudorapidity range in Pb–Pb collisions at the centre-of-mass energy per nucleon pair $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [7]. In this Letter, we study these distributions in the pseudorapidity interval from −3.5 to 5 at a collision energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV as a function of the centrality. Pseudorapidity is defined as $\eta \equiv -\log(\tan(\vartheta/2))$, where ϑ is the angle between the charged-particle trajectory and the beam axis (z-axis). Nuclei are extended objects, and their collisions can be characterised by centrality — the experimental proxy for the un-measurable distance between the centres of the colliding nuclei (impact parameter). A primary particle is a particle with a mean proper lifetime τ larger than 1 cm/c, which is either a) produced directly in the interaction, or b) from decays of particles with τ smaller than 1 cm/c, restricted to decay chains leading to the interaction [8]. In this Letter, all quantities reported are for primary charged particles, though we will omit "primary" for brevity.

With the large pseudorapidity coverage available in ALICE, we can reliably estimate, for all centrality classes, the total number of charged particles produced in the collisions. We therefore also present the first measurement of the total charged-particle multiplicity in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV as a function of the number of nucleons participating in the collisions (N_{part}).

Finally, we transform the measured $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ distribution for the 5% most central collisions into charged-particle rapidity density ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$), and we examine the centre-of-mass energy dependence of the width of that distribution. The rapidity (y) of a particle with energy E and momentum component p_z along the beam axis is defined as $y \equiv \frac{1}{2}\log([E + p_z]/[E - p_z])$. The comparison of the width of the $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y$ at different collision energies provides an insight into the constraints on the overall production mechanism of charged particles.

2. Experimental setup

A detailed description of ALICE and its performance can be found elsewhere [9,10]. In the following, we briefly describe the detectors relevant to this analysis.

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The Silicon Pixel Detector (SPD), the innermost part of the Inner Tracking System (ITS), consists of two cylindrical layers of hybrid silicon pixel assemblies covering $|\eta| < 2$ and $|\eta| < 1.4$ for the inner and outer layers, respectively. Combinations of hits on each of the two layers consistent with tracks originating from the interaction point form *tracklets*.

The Forward Multiplicity Detector (FMD) is a silicon strip detector which, records the energy deposited by particles traversing the it. The detector covers the pseudorapidity regions $-3.5 < \eta < -1.8$ and $1.8 < \eta < 5$, and has almost full coverage in azimuth (φ), and high granularity in the radial (η) direction.

The third detector system used in this analysis is the V0. It consists of two sub-detectors: V0-A and V0-C covering the pseudorapidity regions $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively, each made up of scintillator tiles with a timing resolution < 1 ns. The fast signals from either of V0-A or V0-C are combined in a programmable logic to form a trigger signal and to reject background events. Furthermore, the combined pulse height signal of both sub-detectors forms the basis for the classification of events into different centrality classes [11].

The Zero-Degree Calorimeter (ZDC) measures the energy of spectator (non-interacting) nucleons with two components: one measures protons and the other measures neutrons. The ZDC is located at about 112.5 m from the interaction point on both sides of the experiment [9]. The ZDC also provides timing information used to select collisions in the off-line data processing.

3. Data sample and analysis method

The results presented here are based on data collected by ALICE in 2015 during the Pb–Pb collision run of the LHC at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. About 100 000 events with a minimum bias trigger requirement [12] were analysed in the centrality range from 0% to 90%. The minimum bias trigger for Pb–Pb collisions in ALICE, which defines the so-called visible cross-section, is defined as a coincidence between the A ($z > 0$) and C ($z < 0$) sides of the V0 detector.

The standard ALICE event selection [13] and centrality estimator based on the V0–amplitude [11] are used in this analysis. The event selection consists of: exclusion of background events using the timing information from the ZDC and V0 detectors; verification of the trigger conditions; and a reconstructed position of the collision. As discussed elsewhere [11], the 90–100% centrality class has substantial contributions from QED processes and is therefore not included in the results presented here.

The measurement of the charged-particle pseudorapidity density at mid-rapidity ($|\eta| < 2$) is obtained from a tracklet analysis using the two layers of the SPD. The analysis method used is identical to what has previously been presented [12,14,15]. Note that no attempt is made to correct for known deficiencies, such as deviations in the number of strange particles or transverse momentum (p_{T}) distributions compared to experimental measurements [11,16,17], in the event generators used to obtain the corrections from simulations (e.g., HIJING). It is found, through simulation studies, that tracklet reconstruction first and foremost depends on the local hit density and only weakly on particle mix and transverse momentum. For example, the deficit of strange particles in the event generator effects the result by less than 2%. Since the event generators generally, after detector simulation, produce a local hit density that is consistent with what is observed in data, we observe a correspondence between the tracklet samples of both simulations and data. On the other hand, changing the number of tracklets corresponding to strange particles a postiori to match the measured relative yields dramatically biases the simulated tracklet sample away from the measured, thus entailing systematic uncertainties that are beyond the effect of the known event generator deficiencies, and

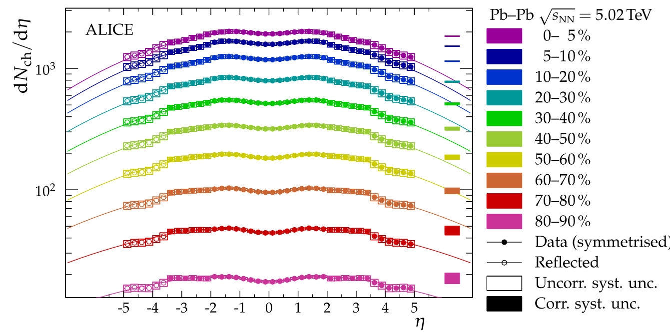

Fig. 1. [Colour online.] Charged-particle pseudorapidity density for ten centrality classes over a broad η range in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Boxes around the points reflect the total uncorrelated systematic uncertainties, while the filled squares on the right reflect the correlated systematic uncertainty (evaluated at $\eta = 0$). Statistical errors are generally insignificant and smaller than the markers. Also shown is the reflection of the $3.5 < \eta < 5$ values around $\eta = 0$ (open circles). The line corresponds to fits of the difference between two Gaussians centred at $\eta = 0$ (f_{GG}) [7] to the data.

as such do not improve the accuracy of the measurements. Instead, variations on the event generators are used to estimate the systematic uncertainties as detailed elsewhere [12,14,15].

In the forward regions ($-3.5 < \eta < -1.8$ and $1.8 < \eta < 5$), the measurement is provided by the analysis of the deposited energy signal in the FMD. The analysis method used is identical to what has previously been presented [7,14]: a statistical approach to calculate the inclusive number of charged particles; and a data-driven correction — derived from previous satellite-main collisions — to remove the large background from secondary particles.

4. Systematic uncertainties

For the measurements at mid-rapidity the sources and dependencies of the systematic uncertainties are detailed elsewhere [7,12,15]. The magnitude of the systematic uncertainties is unchanged with respect to previous results, and amounts to 2.6% at $\eta = 0$ and 2.9% at $\eta = 2$, most of which is correlated over $|\eta| < 2$, and largely independent of centrality.

The systematic uncertainty on the forward analysis is evaluated using the same technique as for previous results [7]. We find that the uncertainty is uncorrelated across η an that it amounts to 6.9% for $\eta > 3.5$ and 6.4% elsewhere within the forward regions.

The systematic uncertainty on $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ due to the centrality class definition is estimated as 0.6% for the most central and 9.5% for the most peripheral class [15]. The uncertainty is estimated by using alternative centrality definitions based on SPD hit multiplicities and by varying the fraction of the visible hadronic cross-section. The 80–90% centrality class has some residual contamination from electromagnetic processes detailed elsewhere [11], which gives rise to a 4% additional systematic uncertainty on the measurements.

In summary, the total systematic uncertainty varies from 2.6% at mid-rapidity in the most central collisions to 12.4% at the very forward rapidities for the most peripheral collisions.

5. Results

Fig. 1 presents the charged-particle pseudorapidity density as a function of pseudorapidity for ten centrality classes. The measurements from the SPD and FMD are combined in regions of overlap ($1.8 < |\eta| < 2$) between the two detectors by taking the weighted average using the non-shared uncertainties as weights. Finally, based on the symmetry of the collision system, the result is symmetrised around $\eta = 0$, and extended into the non-measured

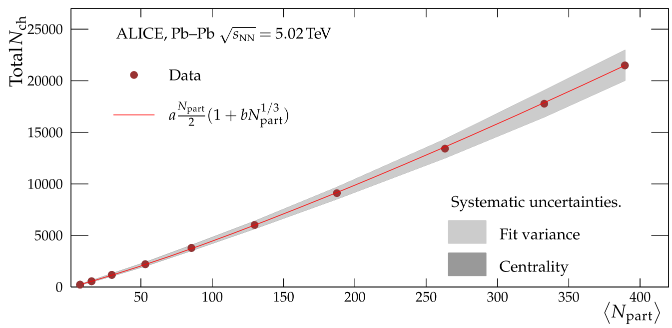

Fig. 2. [Colour online.] Total number of charged particles as a function of the mean number of participating nucleons [11]. The total charged-particle multiplicity is given as the integral over $dN_{ch}/d\eta$ over the measured region ($-3.5 < \eta < 5$) and extrapolations from fitted functions in the unmeasured regions. The contribution from unmeasured η regions amounts to $\approx 30\%$ of the total number of charged particles. The uncertainty on the extrapolation to the unmeasured pseudorapidity region is smaller than the size of the markers. The contribution to the systematic uncertainties from the centrality determination and electromagnetic processes are vanishing compared to the contribution from the largest differences between the fitted functions. A function inspired by *factorisation* [18] is fitted to the data, and the best fit yields $a = 51.5 \pm 7.3$, $b = 0.16 \pm 0.05$.

region $-5 < \eta < -3.5$ by reflecting the $3.5 < \eta < 5$ values around $\eta = 0$. Complementing result previously reported at mid-rapidity [15], we find $dN_{ch}/d\eta|_{|\eta|<0.5} = 17.52 \pm 0.05(\text{stat}) \pm 1.84(\text{sys})$ and $N_{part} = 7.3 \pm 0.1$ in the 80–90% centrality class.

The measured distributions are fitted with four functions f_{GG}, f_P, f_T, and f_B [7], which are the difference of two Gaussian distributions centred at $\eta = 0$; a parametrisation proposed by PHOBOS [18]; a trapezoidal form; and a plateau connected to Gaussian tails, respectively. To extract the total number of charged particles, we calculate the integral and uncertainty from the data in the measured region and use the integrals of the fitted functions in the unmeasured regions up to the beam rapidity $\pm y_{beam} = \pm 8.6$. As for the previous measurements at $\sqrt{s_{NN}} = 5.02$ TeV, the central value in the unmeasured regions ($-8.6 < \eta < -3.5$ and $5 < \eta < 8.6$) is taken from the fit of the function f_T, while the uncertainty is evaluated as the largest difference between the fitted functions scaled by $1/\sqrt{3}$ [7,14]. The total charged-particle multiplicity is shown in Fig. 2 versus the mean number of participating nucleons ($\langle N_{part} \rangle$) estimated from a Glauber calculation [11,15]. After removing correlated systematic uncertainties, we observe an increase in the total number of charged particles of $(27 \pm 4)\%$ with respect to the measurements at $\sqrt{s_{NN}} = 2.76$ TeV [7] for all centrality classes. The line shown in Fig. 2 corresponds to a fit of a function inspired by factorisation [18]. The function illustrates scaling by number of participant pairs, with a small perturbation proportional to the cubic root of the number of participants. As the number of nucleon–nucleon collisions (N_{coll}) scales roughly like the square of the number of participants $N_{coll} \approx N_{part}^2$ [19], we see no indication of scaling by number of nucleon–nucleon collisions. The observed total N_{ch} dependence on $\langle N_{part} \rangle$ provides no evidence of any significant increase in the number of hard scatterings between the participating nucleons and partons.

In Fig. 3, we compare the charged-particle pseudorapidity density for the 0–5% most central collisions to three models: HIJING [20]; EPOS–LHC [21]; and KLN [22,23], also for the 0–5% most central, except for KLN which is shown for the 0–6% centrality class. Two versions of HIJING are used: version 1.383, with jet quenching disabled, shadowing enabled, and a hard p_T cut-off of 2.3 GeV; and the newer version 2.1 [24]. Both are two-component models with a soft and hard sector defined by a p_T cut-off separating the two. In the 2.1 implementation, HIJING uses an upgraded parametrisation of the nuclear parton distribution func-

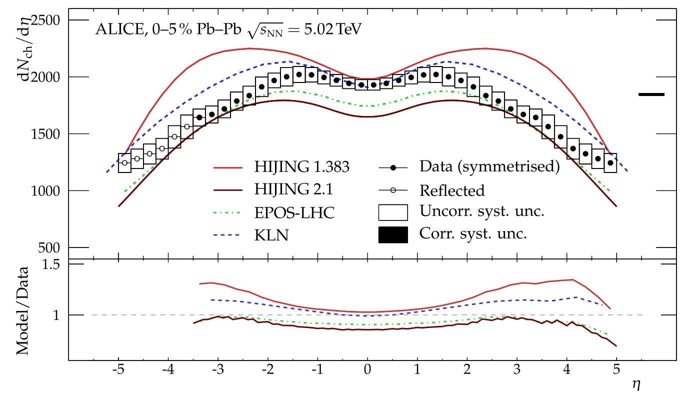

Fig. 3. [Colour online.] Comparison of $dN_{ch}/d\eta$ in the 0–5% (0–6% for KLN) most central collisions of two versions of HIJING, KLN, and EPOS–LHC model calculations to the measured distribution.

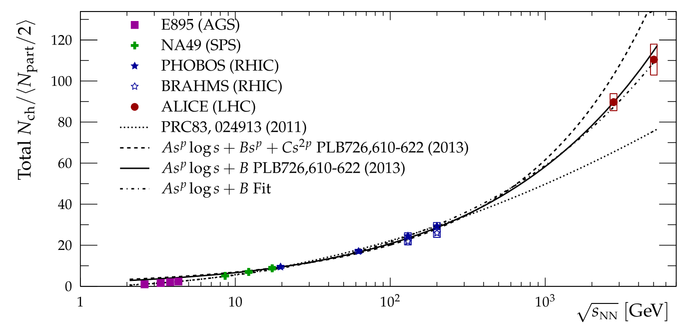

Fig. 4. [Colour online.] Total number of charged particles as a function of $\sqrt{s_{NN}}$ for the most central collisions at AGS (0–5% Au–Au) [25,26], SPS (0–5% Pb–Pb) [27,28], RHIC (0–5% and 0–6% Au–Au) [18,29,30], and LHC (0–5% Pb–Pb) [14]. The dotted, dashed, and full lines are extrapolations from fits to lower energy results [14], while the dash-dotted line is a fit over all energies, including $\sqrt{s_{NN}} = 5.02$ TeV.

tions. This results in a larger cross section for soft processes and a smaller cross section for jet production. The KLN model is based on Colour-Glass-Condensate initial conditions, while EPOS-LHC uses so-called parton-ladders which hadronise in a medium. While none of the three models describe the measured charged-particle pseudorapidity density over the full pseudorapidity range, we observe some differences: HIJING 1.383 over-predicts the charged-particle production especially away from $\eta \approx 0$; EPOS–LHC and HIJING 2.1 consistently under-predict the charge-particle production; whereas KLN, EPOS–LHC, and HIJING 2.1 give a shape reasonably close to the observed distribution. Not shown in Fig. 3, for both HIJING 1.383 and EPOS–LHC, these observations hold over all centrality classes i.e., HIJING 1.383 consistently produces far too many particles away from mid-rapidity and EPOS–LHC consistently under-predicts the charged-particle yield over the full η range. These trends become increasingly more pronounced for more peripheral collisions.

Fig. 4 shows the total number of charged particles produced in the most central heavy-ion collisions as a function of the collision energy, ranging from $\sqrt{s_{NN}} = 2.6$ GeV to 5.02 TeV [14]. The dotted, dashed, and full-drawn lines in the figure represent extrapolations from lower energy results to the current top LHC energy of $\sqrt{s_{NN}} = 5.02$ TeV. None of these predictions fully describe the data. A refit of the simple model of a logarithmic-dampened power-law in the square collision energy (s) including from the lowest to the highest energy results, shown as the dash-dotted line, does accurately describe the total number of charged particles at all available energies.

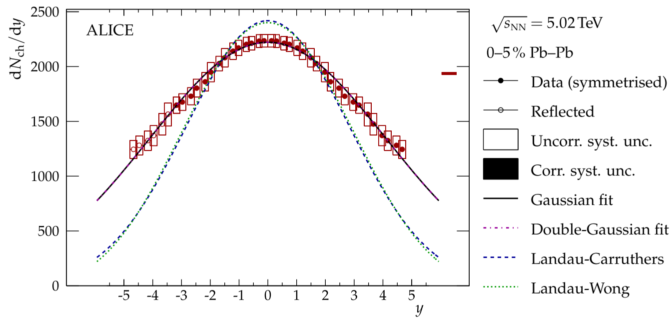

Fig. 5. [Colour online.] Estimate of dN_{ch}/dy in the most central (0–5%) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Also shown are the Landau–Wong [31], Landau–Carruthers [32], Gaussian, and double-Gaussian distributions.

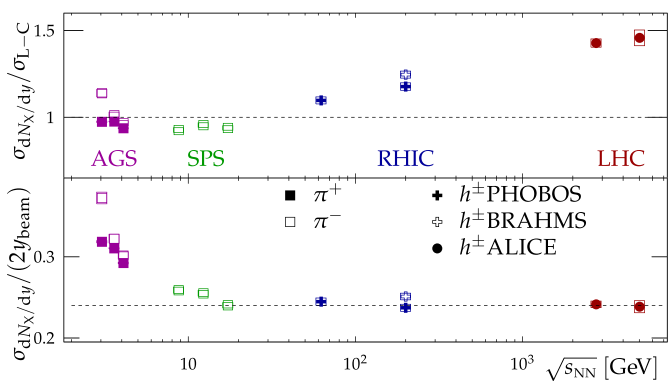

Fig. 6. [Colour online.] Scaling behaviour as a function $\sqrt{s_{NN}}$ of the width of the charged-particle or -pion rapidity-density distribution with respect to the Landau–Carruthers width (top) and rapidity range (bottom). Charged-pion points from AGS and SPS are adapted from the literature [33], while the PHOBOS (filled crosses) [34] and BRAHMS (open crosses) [30] charged-hadron points are translated from the corresponding $dN_{ch}/d\eta$ results.

We can calculate the Jacobian transform from η to rapidity y by assuming the same transverse momentum distribution of (anti-)protons, and charged kaons and pions, and the same particle ratios in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as in $\sqrt{s_{NN}} = 2.76$ TeV. The result is presented in Fig. 5 for the 0–5% most central collisions. The effect on the Jacobian from the change of p_T spectra and particle ratios when increasing the collision energy by almost a factor two is evaluated using the EPOS–LHC model [21]. It is found, that the effect is at most 3‰ on both dN_{ch}/dy and y — much smaller than the systematic uncertainty and η resolution of the analysis. Fig. 5 also shows the expected charged-particle rapidity densities from the Landau–Carruthers [32] and Landau–Wong [31] models, both assuming Landau hydrodynamics i.e., based on a reaction scenario with full stopping of the reaction partners and a subsequent thermodynamic evolution. The measurements, however, are seen to be consistent with a Gaussian distribution with a width of 4.12 ± 0.10, much wider than the width expected from the two models. A best parameter fit of the sum of two Gaussian distributions with means symmetric around $y = 0$, is indistinguishable from the single Gaussian case.

In the top part of Fig. 6 we compare the widths of the charged-particle or -pion rapidity density distribution extracted from measurements to the expected width $\sigma^2_{L\text{-}C} = \log(\sqrt{s_{NN}}/2m_p)$ from Landau–Carruthers, where m_p is the proton mass, at collision energies ranging from 2.6 GeV up to 5.02 TeV. An increase of $\approx 7\%$ of $\sigma_{dN_X/dy}/\sigma_{L\text{-}C}$ is seen from the $\sqrt{s_{NN}} = 2.76$ TeV ALICE measurements [14]. The full evolution is consistent with an almost linear rise as a function of $\log\sqrt{s_{NN}}$ from the top SPS energy at $\sqrt{s_{NN}} = 17.3$ GeV. It can be shown [35] that the width of the rapidity-density distribution in Landau hydrodynamics scales as $\sigma_{dN_X/dy} \propto 1/(1-c_s^2)$, where c_s is the speed of sound in the matter. The lifetime of the system scales inversely with c_s, and given that the measured width is larger than the predicted by Landau hydrodynamics, it is an indication that, given the considerations above, the lifetime is shorter than suggested.

In the bottom part of Fig. 6 we compare the width of the dN_{ch}/dy distribution to the available rapidity range ($2y_{beam}$). We observe no dependence of this ratio from $\sqrt{s_{NN}} = 17.3$ GeV and upward, indicating that the available phase–space constrains the width of that distribution. The charged-hadron measurements at RHIC (crosses) from the BRAHMS [30] and PHOBOS [34] measurements of $dN_{ch}/d\eta$ are converted to dN_{ch}/dy using the same method as applied to the ALICE data. Previously, charged-pion measurements from BRAHMS have been reported [33]. These data are not included because a re-evaluation using RHIC Run-4 Au–Au data has not been finalised [36].

From the observed s^p scaling of the charged-particle pseudorapidity density at mid-rapidity [15] we expect a 20% increase over $\sqrt{s_{NN}} = 2.76$ TeV in the level of $dN_{ch}/d\eta|_{|\eta|<0.5}$ and from the extracted width of dN_{ch}/dy we observe an additional 7%, consistent with the increase of 27% over $\sqrt{s_{NN}} = 2.76$ TeV in the total number of charged particles produced in $\sqrt{s_{NN}} = 5.02$ TeV collisions.

6. Conclusions

The charged-particle pseudorapidity density is measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV over the psuedorapidity range $-3.5 < \eta < 5$. The total number of charged particles produced is determined owing to the large pseudorapidity acceptance of ALICE. The latter increases by two orders of magnitude from the most peripheral to the most central collisions and scales approximately with the number of participating nucleons. The increase in the total number of charged particles relative to $\sqrt{s_{NN}} = 2.76$ TeV is estimated to be $(27 \pm 4)\%$. The charged-particle rapidity density for the most central collisions is extracted, and the width of that distribution is compared to predictions from the Landau–Carruthers and Landau–Wong hydrodynamic models. It is found that the measured charged-particle rapidity density becomes increasingly wider as a function of collision energy than predicted by Landau hydrodynamics. The width of the charged-particle rapidity density is seen to scale with the beam rapidity, which implies that the available phase space determines the longitudinal extend of the charged-particle production. The phase space dominance starts at the top SPS energy and persist for two orders of magnitude up to the top LHC energy.

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